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Search for 12.6 Millisecond Periodicity in TeV Gamma Rays from Cygnus X-3

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Abstract. Cygnus X-3, an X-ray binary with an orbital period 4.8 hr was seen to be emitting γ-rays with the same period at TeV energies by several groups. In addition the Durham group (Chadwick *et al*. 1985) published their observations on the existence of a pulsar in the Cyg X-3 system, emitting TeV γ-rays with a periodicity of approximately 12.6 ms. We observed this object during 1986 October–November and did not detect any pulsed emission of TeV γ-rays in the range of periods from 12.5850 to 12.5967 ms.

Key words: γ-ray astronomy—X-ray binaries—TeV γ-rays—Cygnus X-3

1. Introduction

The celestial object Cygnus X-3, an X-ray binary (Parsignault *et al*. 1972) with an orbital period $\simeq$ 4.8 hr, was observed to emit also in the infrared (Becklin *et al*. 1973), at TeV and PeV γ-ray energies (see for example, Weekes 1984) with the same periodicity as in the X-ray region. At energies of a few hundred MeV, the SAS-2 satellite group reported (Lamb *et al*. 1977) seeing the emission at the same periodicity while a later satellite experiment, COS-B, with a much larger data base did not find (Hermsen *et al*. 1987) any evidence. The observed luminosities of the object at TeV and PeV energies are 8×10^{35} and 6×10^{36} $\mathrm{erg\,s^{-1}}$ respectively (Weekes 1984), with the latter figure obtained by taking the effect of interstellar absorption (Gould 1983; Cawley & Weekes 1984) by the microwave background radiation into account. It was long suspected that one of the components of the binary system must be a pulsar which would accelerate charged particles that eventually produce TeV and PeV γ-rays at the observed luminosities. Searches (see for example, Damashek *et al*. 1978 and Stokes *et al*. 1985) in the radio wavelength region did not, however, detect any pulsar in the direction of Cyg X-3 in the period range $0.004 \leqslant P \leqslant 3.9$ s. While these negative results could be explained away in terms of the searches not being sensitive to objects having large dispersion measure and the flux values being lower than the detection threshold, the question of the existence of the pulsar persisted.

Chadwick *et al* (1985) operating an atmospheric Cerenkov telescope in Utah (USA) reported seeing pulsed emission of TeV γ-rays with a periodicity of 12.5908 ± 0.0003 ms. Since there was nothing known about the pulsar period prior to their analysis, Chadwick *et al.* had to carry out a parametric search for periodicity in the enormous range 10 ms to 50 s which necessarily involved a very large number of trial periods. For the signal to stand out clearly over trivial chance occurrence probability in the vast number of trials, the signal had to be of sufficient strength and size. On 1983 September 12, the gross counting rate in their detector had gone up sufficiently higher than the average rate which allowed the authors to carry out their parametric search. The authors observed pulsations at the period of 12.5908 ms during two of the 8 observations made during 1983. In each instance, the pulsed emission was seen to occur over a time interval of 7 minutes at an orbital phase $\phi_{4.8\ \mathrm{h}} = 0.625$. Indeed the pulsations were found to occur even over time intervals as short as 1 minute which allowed the authors to establish a correlation between signal strength and counting rate over independent 1 minute intervals. The combined probability that the result was due to chance fluctuations in the cosmic ray shower background (taking all degrees of freedom into account) was given as 3×10^{-7} by the authors. A subsequent search of the data taken earlier during 1982 by the same group also showed evidence (see Fig. 2 of Chadwick *et al.* 1985) for a 12.6 ms pulsar at $\phi_{4.8\ \mathrm{h}} = 0.59$. At a recent workshop on very-high-energy γ-ray astronomy, the same Durham group (Chadwick *et al.* 1987) claimed seeing the pulsar on 1985 October 12 at a period of 12.5928 ms at an orbital phase of $\phi_{4.8\ \mathrm{h}} = 0.55 \pm 0.10$ (Ramana Murthy 1987). Though the Mt Haleakala collaboration (Resvanis *et al.* 1987) presented at the workshop evidence confirming millisecond periodicity over time intervals of the order of 100 s at $\phi_{4.8\ \mathrm{h}} = 0.74$, this report is not confirmed in later and fuller reanalyses described in their paper. In addition, the Mt Hopkins collaboration (Fegan *et al.* 1987) reported at the same meeting that the results of their period search failed to substantiate the result of Chadwick *et al.* (1985). In view of the obvious importance of the topic and the conflicting results, it appeared important to independently check if there is a pulsar in the Cyg X-3 system emitting TeV γ-rays with a 12.6 ms periodicity.

2. Observations and analysis

We observed Cyg X-3 recently at TeV energies using the atmospheric Čerenkov technique at Pachmarhi (longitude: 78°.26 E, latitude: 22°.28N and altitude 1075 m above sea level), India. Details of the technique and apparatus are already published (Ramana Murthy 1980; Vishwanath 1982). We used 3° diameter masks in front of the photomultipliers at the focal plane of the reflectors. Cyg X-3 was tracked for 1 to 2 hours during 7 different runs taken in as many nights during the period 1986 October 27–November 3, for a total of approximately 10 hours. The 4.8 hr phase during our observations was in the range 0.3 to 0.7, with the phase region $0.45 < \phi_{4.8\ \mathrm{h}} < 0.7$ accounting for 60 per cent of the observation. This range in $\phi_{4.8\ \mathrm{h}}$ matches well with the full range of values reported in the past detections as mentioned in the Introduction. The time of occurrence of each event, derived from an accurate (± 30 μs with respect to UTC) clock was recorded to an accuracy of ± 0.05 ms. The observed event times were converted to those at the solar system barycentre.

From the publication of Chadwick *et al.* (1985), the pulsations seem to occur over time spans of as short as 1 minute. We therefore divided all our data into segments of 1 minute duration and performed Rayleigh test (Mardia 1972; Protheroe 1985) on each data segment. We tried 40 periods in the range $12.585 \leqslant P \leqslant 12.5967$ ms with an incremental step of $\Delta P = 3 \times 10^{-7}$ s. Admittedly such a fine step leads to an oversampling by a factor of 9. However, such an oversampling does not mask the signal at all, but lets one detect the growth and decay of the signal with the test period. This search range in period encompasses all the published or reported periods so far. We assumed $\dot{P} = 0$. This assumption is well justified in view of the data set in each trial being limited to 1 minute duration; only $\dot{P}$ in excess of 5×10^{-9} (or 0.15 s yr^{-1}) would have changed the period by more than the step size used in the search, during one minute.

Assuming an arbitrary epoch t_0, the phase of an event occurring at time t is calculated as

$$\phi = \phi_0 + \frac{t - t_0}{P_j}. \tag{1}$$

We make $\phi_0 = 0$, as this does not affect the result. We then compute for each minute and each assumed period P_j the Rayleigh power, Q, as given by

$$Q = \frac{1}{N}\left[\left\{\sum_{i=1}^{N} \cos(2\pi\phi_i)\right\}^2 + \left\{\sum_{i=1}^{N} \sin(2\pi\phi_i)\right\}^2\right]. \tag{2}$$

Here N is total number of events in a given minute.

We have also computed for each minute and for each period (in the same range as used in the Rayleigh test) the traditional phasograms by the epoch-folding method.

Our estimated detection threshold for γ-ray showers is 1.4 TeV. We note that, once the approximate value of the period is known, there is no longer any need to insist on a significant increase in the gross event rate unlike in the situation faced by Chadwick *et al.* (1985) in their discovery paper when nothing was known about the period. In our analysis, we test the possibility that the period can be anywhere in the range 12.585–12.597 ms and may not lie exactly on the straight line in Fig. 7 of Chadwick *et al.* (1987). Likewise, though Chadwick *et al.* (1985) observed the light curve to be broad, we have analysed our data for this possibility (Rayleigh test method) as well as for a possible narrower light curve (epoch folding method). In effect, we did not restrict ourselves to the procedure followed by Chadwick *et al.* (1985) in their discovery paper.

3. Results

At the outset, we want to state that, since our exposure is confined to the 4.8 hr phase region $0.30 \leqslant P \leqslant 0.70$ (and that too unevenly in this range), we will not be able to say anything about the 4.8 hr periodic emission of TeV γ-rays by Cyg X-3. Nor can we say anything about the unpulsed emission of TeV γ-rays as we did not make any drift scans of this region and cosmic-ray induced showers dominate the observed events. We therefore confine our attention to the 12.6 ms periodic emission.

The differential distribution of the Rayleigh power, Q, as computed by us on the basis of our data is shown in Fig. 1. It consists of 23120 entries which is a product of the number of periods (= 40) searched and the number of minutes (= 578) of observation. The quantity $2Q$ for a purely randomly occurring sequence of events with no periodic signal present (null hypothesis) is expected (Protheroe 1985) to be distributed as χ^2 for

2 degrees of freedom, *i.e.*,

$$F(Q)\,dQ = M\,e^{-Q}\,dQ, \quad (3)$$

where M is the total number of entries (23120) and Q is already defined by the Equation (2). The expectation for the null hypothesis is shown by the straight line in Fig. 1. There is a very good agreement between the computed Rayleigh power distribution and the one expected on the basis of null hypothesis.

Leahy, Eisner & Weisskopf (1983) have pointed out that the epoch-folding method of analysis, *i.e.*, constructing a phase histogram on the basis of event times *modulo* the period of pulsations is more sensitive than the Rayleigh test if the pulsar light curve were to consist of a narrow pulse. To investigate this possibility, we subjected our data to the epoch-folding analysis by doing a periodicity scan in the range $12.585 \leqslant P \leqslant 12.5967$ ms incrementing the period by $\Delta P = 3\times10^{-7}$ s. These search parameters a re identical to those used in the Rayleigh test. While calculating the phase of any event, we assumed the same arbitrary epoch t_0 = 48600.0 s UTC on 1986 October 27 (see Equation 1) for the entire data and made $\dot{P}$ = 0. Phasograms with 20 phase bins for each minute's data (total: 578 minutes) for 40 periods were computed and whenever any phasogram showed 4σ or greater excess or deficiency in any of its bins in comparison with the average, the full phasogram, the period and the time were printed out.

The calculations showed a total of 81 cases of phasograms (out of 23120) where a bin showed an excess of $> 4\sigma$ over the average while the expectation on purely random poisson fluctuations basis is 84 cases (=prob. ($>4\sigma$) × no. of minutes × no. of trial

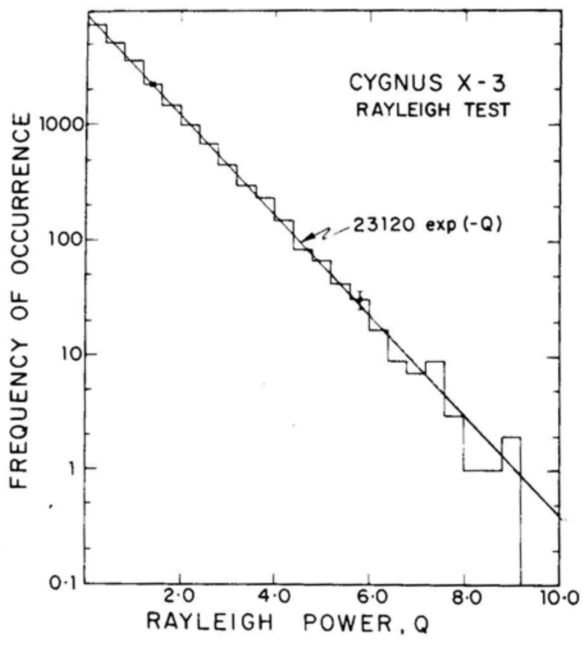

Figure 1. Rayleigh power distribution resulting from search for a periodicity in the range $12.585 \leqslant P \leqslant 12.5967$ ms (40 periods) for 578 minutes' data is shown in the histogram. The straight line is the expectation for the same distribution for null (no signal) hypothesis.

periods × no. of bins). We also note that the excesses are distributed all over the period range that was tried rather than being confined to one particular period as one would expect for a genuine periodicity.

4. Conclusions

We observed Cyg X-3 for approximately 10 hours during the time 1986 October 27–November 3 to see if the object emits TeV γ-rays in a pulsed mode with a periodicity of 12.6 ms. We found no evidence for such an emission either by the Rayleigh test (case of broad light curve) or by the epoch-folding method (case of light curve with a narrow emission peak). The 95 per cent confidence level upper limits obtained by these two methods are 2.4×10^{-9} and 5.8×10^{-10} cm^{-2} s^{-1} respectively for pulsed ($12.585 \leqslant P \leqslant 12.5967$ ms) emission of γ-rays over time intervals of the order of 1 minute by Cyg X-3. Expressed as a fraction of cosmic ray shower rate (with a 3° diameter viewing aperture), showers due to pulsed γ-rays were less than 12 per cent in any minute during the entire observation.

Our conclusion that there was no pulsed emission during the period 1986 October 27–November 3 does not necessarily conflict with the claim of Chadwick *et al*. (1985) on two counts: (i) the epoch of our observation is different from theirs, and (ii) the duty cycle for 12.6 ms pulsed emission seems to be quite low, *e.g*., the object pulsed only for 7 minutes during 6 hours of observation by Chadwick *et al*. (1985) and it is just possible that the object failed to pulse during our observations. It appears, therefore, important to continue observations on this object to confirm independently the 12.6 ms pulsed emission in TeV γ-rays first claimed by the Durham group (Chadwick *et al*. 1985).

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